Characteristics of dietary sugars compared with their roles in body metabolism

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Based on our 2-yr experience in teaching digestive physiology at the Osijek Faculty of Food Technology in Osijek, Croatia, this article is an attempt to improve students’ understanding of carbohydrate metabolism. The presented material is adapted from a Croatian version prepared for students of food technology attending the Digestive Physiology course in their fourth year, after the completion of chemical and biochemical courses that enabled them to understand carbohydrate terminology and metabolism. Students are also expected to show some knowledge regarding digestive tract function and insulin actions. In case of any doubt, students are encouraged to ask questions.

The text is given to students as reading material for a discussion during seminars on carbohydrate metabolism, usually scheduled for the following week. Students can use their textbooks and other references listed in the material, most of them chosen due to their availability as Web sources. Since <20 students were in both classes, they spontaneously shared duties among them, so all sources were found by at least 1 student, which is an expected behavior for a group of fourth-year students. Nevertheless, they showed interest in this topic, which was directly related to their main interest, food technology. We believe that the same or similar material can be helpful in teaching digestion to students of various biomedical programs.

The goal was to gain a more comprehensive view of this topic through a reinterpretation of sugar-related facts taken from their textbooks. After completing the seminar, the student is expected to be able to compare and contrast the digestion of simple sugars by the gastrointestinal tract and the implications for water balance. The student will interpret the actions of insulin and which foods have the greatest effect on insulin release.

Text for Students

Characteristics of dietary sugars and their roles in body metabolism. Please use your textbooks and other sources listed in the References.

Sugars in food and beverages. Human carbohydrate metabolism is determined by the presence of different sugars in our diet (Table 1). Most of the carbohydrate calories we eat come from starch, a polymer of glucose.

Sucrose, or “cane sugar” in the United States and “table sugar” in Europe, is another important sugar in the Western diet. It is a disaccharide, as molecules of sucrose are dimers that consist of one glucose molecule and one fructose molecule. Sucrose is produced from sugarcane and sugar beets but is also found in fruits. Lactose is the main disaccharide (glucose + galactose) in milk.

Both glucose and fructose as monomers (monosaccharides) can naturally be found along with sucrose in fruits. These two monosaccharides are the main sugars in honey. An artificial mixture of them is produced from corn starch as high-fructose corn syrup (HFCS), which is used as a soft drink and food sweetener.

Sugar ingestion and osmolarity of the intestinal contents. Oligosaccharides (sucrose, lactose, maltotriose, etc.) and particularly monosaccharides (glucose, fructose, and galactose) are all osmotically active molecules. From the beginning of the duodenum throughout the rest of the small intestine, normal digestion sustains the osmotic pressure of the intestinal contents equal to the plasma (1), with no sudden changes in the osmolarity of the contents.

Correction of osmolarity starts in the stomach through mixing with the gastric juice, but a combination of fluid secretion and absorption of water and solutes in the small bowel maintains the isotonicity of the intestinal contents. Gastric emptying of hypertonic solutions is slowed via the enterogastric reflex, and this is triggered via osmoreceptors in the duodenum. As food is slowly digested in the small bowel, new osmotically active molecules are continuously liberated from food particles, but some of them are also absorbed, so the additional dilution volume by osmosis often remains limited. Water follows the absorption of osmotically active molecules, and this process maintains the isotonicity of the intestinal contents along the small bowel. Thus, the absorption of salt, various sugars, and other substances (e.g., amino acids and water-soluble vitamins) all help in fluid traffic. Due to cotransport with Na+ across the mucosal membrane, many sugars and amino acids depend on Na+ movement. This net solute transport is important when considering the quantity of water that can be moved into the bloodstream.

The presence of a hypertonic concentration of small sugar molecules in the gut requires some intestinal fluid to dilute the gut content to isotonicity. Intact starch is not osmotically important since it is a huge molecule, but during the enzymatic digestion of starch, many small molecules form and act as osmotic particles.

Three clinical topics are related to the dilution of the intestinal contents due to osmotic forces. The first is postprandial hypotension, which is, at least partially, caused by osmotic water traffic into the intestinal lumen (4). Second, in diarrheal patients, hypertonic drinks with a high sugar concentration can worsen diarrhea, as they draw water out of the body and into the intestine; thus, these should never be used for peroral rehydration (2).
Table 1. Characteristics of dietary sugars compared with their roles in body metabolism

<table>
<thead>
<tr>
<th>Dietary Sugar Source</th>
<th>Sugar Molecules</th>
<th>Enzymes</th>
<th>Monosaccharides</th>
<th>Intestinal Mucosa Transporter</th>
<th>Water Absorption</th>
<th>Stimulation of Insulin Secretion</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>Starch</td>
<td>Glucose polymer</td>
<td>Pancreatic and intestinal glycosidases</td>
<td>Glucose</td>
<td>SGLT-1</td>
<td>Rapid</td>
<td>Yes</td>
<td>Speed of enzymatic digestion limits the increase in glycemia, osmotic load, and insulin secretion</td>
</tr>
<tr>
<td>Table sugar</td>
<td>Sucrose</td>
<td>Acidic hydrolysis and glycoside hydrolase</td>
<td>Glucose and fructose</td>
<td>SGLT-1 for glucose and GLUT5 for fructose</td>
<td>Rapid for glucose and slow for fructose</td>
<td>Yes for glucose and no for fructose</td>
<td>Fructose does not stimulate insulin secretion and can be converted into glucose or in triglycerides</td>
</tr>
<tr>
<td>Breast milk</td>
<td>Lactose</td>
<td>Lactase</td>
<td>Glucose and galactose</td>
<td>SGLT-1</td>
<td>Rapid</td>
<td>Yes for glucose and no for galactose</td>
<td>Isotonicity and rapid absorption of both sugars facilitate hydration. Galactose does not stimulate insulin secretion, and its slow conversion to glucose acts as a backup sugar between feedings</td>
</tr>
<tr>
<td>Honey</td>
<td>Mostly monosaccharides</td>
<td>None</td>
<td>Glucose and fructose</td>
<td>SGLT-1 for glucose and GLUT5 for fructose</td>
<td>Rapid for glucose and slow for fructose</td>
<td>Yes for glucose and no for fructose</td>
<td>Hypertonicity requires the dilution of intestinal fluid or fresh water ingestion. Fructose does not stimulate insulin secretion and can be converted into glucose or in triglycerides</td>
</tr>
<tr>
<td>High-fructose corn syrup</td>
<td>55% Fructose and 45% glucose</td>
<td>None</td>
<td>Glucose and fructose</td>
<td>SGLT-1 for glucose and GLUT5 for fructose</td>
<td>Rapid for glucose and slow for fructose</td>
<td>Yes for glucose and no for fructose</td>
<td>Hypertonicity requires the dilution of intestinal fluid or fresh water ingestion. Fructose does not stimulate insulin secretion and can be converted into glucose or in triglycerides</td>
</tr>
<tr>
<td>Various fruits</td>
<td>Monosaccharides and sucrose</td>
<td>For sucrose: acidic hydrolysis and glycoside hydrolase</td>
<td>Glucose and fructose</td>
<td>SGLT-1 for glucose and GLUT5 for fructose</td>
<td>Rapid for glucose and slow for fructose</td>
<td>Yes for glucose and no for fructose</td>
<td>Fructose does not stimulate insulin secretion and can be converted into glucose or in triglycerides</td>
</tr>
</tbody>
</table>

Information was based mainly on textbook data (1). SGLT-1, Na⁺-glucose cotransporter 1; GLUT5, glucose transporter 5.
The World Health Organization recommends an oral rehydration solution that contains 3 g salt, 75 mM Na\(^+\), 65 mM Cl\(^-\), 20 mM K\(^+\), 10 mM citrate, and 75 mM glucose to encourage the absorption of water accompanying solute co-transport. This is a hypotonic solution (245 mosM) optimized for maximal fluid intake. Hypotonic solutions made of salt and glucose polymers from rice might be even better, probably due to the slowed release of glucose molecules through the enzymatic digestion of polymers.

The last example is often found in patients after gastric surgery, where a sudden hyperosmotic load in the small bowel can cause “dumping syndrome” due to an uncontrolled, rapid entry of hypertonic gastric contents into the small intestine, where so much water moves into the gut that significant circulatory hypovolemia and arterial hypotension result (7).

It can be presumed that the expected total intestinal fluid volume after the ingestion of a hypertonic drink is slightly less than the sum of the ingested volume and the intestinal fluid needed for dilution. If so, any hypertonic drink will initially take some water out of the body into the small bowel. The fate of ingested sugars in the small bowel. All sugars are split to monosaccharides through enzymatic action. Breast milk is isotonic, and it does not require any intestinal fluid for dilution. During the first 6 mo of life, the small bowel can absorb intact milk proteins by transcytosis and enzymatically split lactose. The resulting monosaccharides are both quickly absorbed, and water follows by osmosis. Glucose and galactose are absorbed in the small intestine accompanied by Na\(^+\) through active cotransporters [Na\(^+\)-glucose transporter (SGLT)-1], so any water from drinks containing these sugars can be absorbed into the bloodstream in <2 h (1). This means that any breast-fed baby is easily hydrated by breast milk. Splitting of lactose is often reduced, or even lacking, in adults of many ethnic groups. These adults often complain of digestive symptoms due to a deficiency of lactase and the resulting insufficient digestion of lactose molecules, which are left unsplit and later digested by colonic bacteria.

Fructose differs from glucose and galactose in the mechanism and speed of absorption. It is absorbed through a facilitated diffusion transporter [glucose transporter (GLUT)5] (6). Absorbed molecules of fructose and glucose leave intestinal cells by GLUT2 transporters at their basolateral membrane. This rapid clearance of fructose from intestinal cells maintains facilitated diffusion, which depends on keeping intracellular fructose concentration low. In normal adults, fructose is absorbed along the entire small bowel, so the absorption can take up to 4 h. The consequence is that after fruit or a sucrose-sweetened drink, some water will be delayed in absorption, waiting for fructose to be slowly absorbed. After the ingestion of drinks that contain sucrose, one-half of the ingested water will rapidly follow glucose absorption, but the rest occurs after slow fructose absorption.

Many isotonic “sport” drinks contain low amounts of carbohydrates (near 6%) and electrolytes (3), and various combinations of monosaccharides and sucrose are often used to obtain isotonicity. The idea behind sport drinks is to allow the absorption of Na\(^+\) and carbohydrates without the initial dilution of osmolality by the intestinal fluid, aiming to achieve rapid hydration and energy replenishment.

HFCS is produced by splitting starch into glucose molecules that are partially enzymatically converted to fructose. Typical HFCS for soft drinks contains 55% fructose and 45% glucose. Compared with pure sucrose solutions, HFCS-containing soft drinks contain twice as many osmotically active molecules for the same amount of sugar. Due to the high initial osmolality, the HFCS-containing soft drink is an important osmotic challenge. The ingestion of 0.5 liters of hypertonic HFCS-containing drink with 800 mosM is expected to trap a total volume of >1 liter of isotonic contents in the small bowel (0.5 liters is ingested and the rest is diluted by the intestinal fluid). Some 45% of this enlarged fluid volume is expected to be absorbed within 2 h (together with glucose absorption). The rest of it remains in the small bowel for about 4 h, due to slow fructose absorption.

Important physiological features of monosaccharides. As shown in Table 1, specific features of various monosaccharides are related to their role in our metabolism.

For instance, lactose is a dimer of two actively absorbed sugars. Since isotonic breast milk normally contains nearly 70 g/l lactose, it would contain many fewer carbohydrates and energy if monosaccharides were the main sugars. The isotonicity of breast milk, rapid enzymatic splitting of lactose, and active absorption of the resulting monosaccharides all help in rapid fluid absorption. A possible additional advantage of galactose over glucose is that it does not stimulate insulin secretion. Thus, galactose reduces the risk of hypoglycemia due to increased insulin secretion. In addition, the conversion to glucose is controlled by the liver, so it can be a backup glucose source between breast feedings.

Sucrose is probably the most abundant sugar dimer in our diet. Compared with honey, or to HFCS, it has just a half of the particles osmotically. This allows the ingestion of large quantities of sucrose drinks to be drunk at once without disturbing the extracellular fluid pool. For instance, most sucrose drinks are near 400 mosM, so they require smaller amounts of water to reach isotonicity (0.5 liters needs only 0.16 liters of water to become 300 mosM). One-half of the total intestinal volume (near 0.33 liters) will be quickly absorbed with glucose, and the rest will slowly follow fructose absorption. In this way, the fluid volume load is optimized within 3 or 4 h, allowing larger volumes to be taken at once.

HFCS-containing soft drinks are usually hypertonic [near 700–800 mosM (5)] due to their monosaccharide content. The dilution to isotonicity takes much more water compared with the same concentration of sucrose. After 0.5 liters of soft drink with HFCS (800 mosM) are ingested, it needs to be diluted to a total volume of >1 liter to become isotonic. Some 45% of this volume (near 0.5 liters) is expected to be absorbed within 2 h, along with glucose absorption. At that moment, the initially trapped volume from the extracellular fluid pool has just been regained, so that actual hydration takes the next 2 h, along with slow fructose absorption. Nobody should then be surprised that thirst is often sooner and better satisfied by fresh water than by hyperosmolar soft drinks.

REFERENCES

